INSTRUMENT MAKING, METROLOGY AND INFORMATION-MEASURING DEVICES AND SYSTEMS

METHOD FOR CONTROL THE MECHANICAL PARAMETERS OF OVERHEAD POWER LINES BASED ON IMPROVED INCLINOMETRY

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Abstract: Structural elements of overhead power transmission lines are experiencing both horizontal and vertical loads. Wires and cables are elements of the overhead power line, on which changes in mechanical loads are observed to a greater degree. This occurs due to the change in the tension force of the wire/cable depending on the temperature and the formation of icy-rime deposits on it, as well as fluctuations in wind gusts. The article describes the most common systems and methods for determining the mechanical loads on an overhead power transmission line. A method is proposed for calculating the mechanical loads on an overhead transmission line based on mathematical models of a flexible wire, rope and a model for determining ice deposits on wires, taking into account the rotation of the wire/cable around its axis. A comparison of the improved inclinometry method with the method developed earlier for the case of formation of ice deposits on the S-50 cable has been carried out. A comparison was made on the error in determining the tension of the S-50 ground-wire protection cable using the method developed to control the mechanical parameters of overhead power lines, which takes into account the wire/cable rotation around its axis and the method for determining icy-rime deposits developed earlier. The developed method allows determining the elongation of the wire/cable in the span with one anchor support, as well as the strength of its tension with greater accuracy. However, additional clarification is required due to the influence of the wind, the formation of icy-rime deposits of various shapes, as well as the structural limitations of the wire/cable rotation when attaching it to the support.

Keywords: overhead power line, overhead line monitoring, mechanical loads, cable rotation, rotation of ground wire, icy-rime deposits, icing.

МЕТОДИКА КОНТРОЛЯ МЕХАНИЧЕСКИХ ПАРАМЕТРОВ ВОЗДУШНЫХ ЛИНИЙ ЭЛЕКТРОПЕРЕДАЧИ НА ОСНОВЕ УЛУЧШЕННОГО ИНКЛИНОМЕТРИЧЕСКОГО МЕТОДА

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Резюме: *Конструктивные элементы воздушных линий электропередачи испытывают как горизонтальные, так и вертикальные нагрузки. Провода и тросы являются элементами воздушной линии, на которых в большей степени наблюдаются изменения механических нагрузок ввиду изменения силы натяжения провода/троса в зависимости от температуры и образования на нём гололёдно-изморозевых отложений, а также колебаний от порывов ветра.В статье описаны наиболее распространенные системы и методики определения механических нагрузок на воздушной линии электропередачи. Предлагается методика расчёта механических нагрузок на воздушной линии электропередачина основе математических моделей гибкой нити, каната и модели определения гололёдных отложений на проводах/тросах, учитывающая вращение провода/троса вокруг своей оси.Проведено сравнение улучшенного инклинометрического метода с методом, разработанным ранее для случая образования гололёдных отложений на тросе С-50. Оценены погрешности при определении силы тяжения грозозащитного троса С-50предлагаемой методикой контроля механических параметров воздушных линий электропередачи, учитывающей вращение провода/троса вокруг своей оси, и методикой определения гололёдно-изморозевых отложений, разработанной ранее. Разработанная методика позволяет определить удлинение провода/троса в пролёте с одной анкерной опорой, а также силу его тяжения с большей точностью, однако требует дополнительного уточнения, связанного с влиянием ветра, образованием гололёдно-изморозевых отложений различной формы, а также конструктивными ограничениями вращения провода/троса при креплении его к опоре.*

Ключевые слова: *воздушная линия электропередачи, мониторинг воздушных линий,механические нагрузки, вращение провода, вращение грозозащитного троса, гололедно-изморозевые отложения, гололед.*

Introduction

Electrical energy is transferred from power plants or substations to the consumer via power lines (mainly overhead), which are part of the electrical system. An overhead power line is a device for transmitting electrical energy through wires located in the open air and secured with insulators and linear fittings to the supports. In addition, lightning protection cables are also used on overhead lines.

The length of overhead power lines in the Russian Federation is over 2.8 million km. The power grid is rapidly becoming obsolete. The level of equipment wear reaches 70% [1]. At the same time, due to the increase in electricity consumption and the commissioning of new sections of overhead power lines, the need for a full-fledged survey to prevent emergency situations increases.

All elements of overhead power lines experience mechanical stress and can be damaged if their mechanical strength limit is exceeded.

Structural elements of overhead power lines experience both horizontal (for example, mechanical stresses in a stretched wire/cable) and vertical loads (for example, from its own weight

or the weight of the wire/cable). Wires and cables are elements of the overhead line on which changes in mechanical loads are observed to a greater degree due to changes in the tension of the wire/cable depending on temperature and the formation of icy-rime deposits on it [2], as well as fluctuations from wind gusts. The main mechanical stresses in the wire/cable of the overhead line are associated with its extension. With an increase in the tensile strength of the wire or rods (cores) of which it is made, its tension also increases.

Exceeding the tensile strength of an overhead power line element can lead to its damage: wire/cable breakage, failure or breakdown of the insulator, interphase short circuit due to wire "dancing" and others.

Mechanical overload of a power line structural element can occur due to the appearance of icy-rime deposits (IRD), the development of fatigue of the air power transmission line structural element, errors in the construction of the line, as well as repair and restoration work. Among the listed reasons, the appearance of IRD is accompanied by the most serious consequences. Therefore, in the future, this problem will catch special attention.

According to the map of ice loads, the Republic of Tatarstan belongs mainly to the second risk group (the normative ice wall thickness on a wire/cable is at least 15 mm). However, the Bugulminsky district, for example, belongs to the fourth, most dangerous group (the normative ice wall thickness on the wire/cable is at least 25 mm). Problems with ice formation were also detected in Leninogorsk, Nurlat and Almetyevsk regions. The number of temperature transitions through 0 °C increased, which led to an increase in the probability of ice formation, since icy-rime deposits on the wires/cables of power lines are formed when supercooled drops of rain, drizzle or fog freeze at temperatures from 0 °C and below [3]. During a relatively mild winter, with a sharp difference in ambient temperature from positive to negative, drops of water settle on the wires/cables and an avalanche-like process of formation of a thick ice crust begins, reaching a thickness of several tens of millimeters, which significantly increase weights of wires/cables.

Deposits of ice, rime and wet snow pose a great danger to the normal operation of overhead transmission lines (OTL). They can cause: a) misalignment of wires and cables and their reprochement with each other; b) reprochement of wires and cables during a jump due to non-simultaneous discharge of ice; c) intense dancing, causing short circuits between wires and between wires and cables, burns of wires and cables, and in some cases damage to linear fittings and fixtures; d) a significant overload of wires and cables and their breaks; e) destruction of supports as a result of breakage of wires and cables during overloading from ice, when unbalanced loads on supports from remaining whole wires and cables significantly exceed the calculated ones, as well as when ice is combined with strong wind; f) overlap of the linear insulation of overhead lines during ice melting, due to a significant decrease in the ice discharge characteristics of insulators as compared to moisture discharge characteristics, which usually select the required level of linear insulation [2].

Thus, it is necessary to accurately localize a site or defect that is problematic with ice, since it is often difficult to travel along overhead lines (deep snowdrifts; natural barriers, i.e. marshy terrain; relief, etc.), and the speed of preventing/eliminating an emergency directly related to the losses incurred.

1. Overview of existing methods and means of determining mechanical loads on an overhead power line

Wires and cables suspended to the supports of an overhead power line are constantly exposed to a vertical load from its own weight, evenly distributed along the length of the line. In addition, other loads can affect them: vertical from ice and horizontal from wind. Therefore, the task of determining mechanical loads on an overhead power line from a practical point of view is inextricably linked with the determination of ice-wind loads. Therefore, it is necessary to consider the methods for identifying and monitoring these types of loads.

The following systems based on stationary devices are used to monitor the state of overhead lines: *CAT-1* (USA) [4], *DiLin* (RF) [5], *Astrose* (Germany) [6], *LINDSEY* (USA) [7], etc.

The *CAT-1* system monitors weather conditions and mechanical loads at the points of wire suspension to the support. The system is quite simple, but due to the patented analysis algorithms it is possible to determine such OTL parameters as: sag arrow, presence of IRD. The main disadvantage of this system is the use of strain gauges mounted on the traverse of the supports, which complicates the installation of the *CAT-1* system [8].

The operation of the *DiLin* system (RF) [9] is based on the frequency method [10,11] for controlling ice formation on overhead lines. Monitoring the presence of icy-rime deposits on overhead line wires is determined by the change in the speed of the electromagnetic field wave along the power line wire. The appearance of ice on the wires is equivalent to the appearance of a large number of short-circuited circuits covering the linear wire in the icing zone. With an increase in the icing zone of wires and the thickness of the ice layer, the influence of these "active - inductive" circuits also increases. This, in turn, leads to an increase in the wave impedance of the overhead line. The active component of the resistance of icy contours leads to an increase in the attenuation of the amplitude of high-frequency signals moving along the line. The reactive resistance of the ice contours slows down the speed of the electromagnetic field wave along the line wires. However, this method has several disadvantages: a high error in the localization of defect sites (up to kilometers); increased influence of connections to the overhead line and environmental factors (the internal resistance of the line changes, which affects the reflected signals) [10].

The *LINDSEY* (USA) [7] and *Astrose* (Germany) [6] systems have proven themselves best of the systems for monitoring the state of overhead lines by indirect methods. They include a tilt angle sensor, a temperature sensor and a current sensor, which allows determining the mechanical loads and parameters of the overhead line [11]. *LINDSEY* and *Astrose* are very informative and form a self-organizing wireless data network. However, these systems have a number of drawbacks: the mathematical model does not allow tracking the icing process, does not take into account the hauling of the wire between adjacent spans, as well as the change in the overhead line geometry depending on the wire temperature [8].

Thus, two methods are mainly used to calculate the mechanical loads of overhead power lines: direct determination (using tensometric sensors) or indirect (inclinometry methods, which are based on the angle of the wire).

2. Improved inclinometry method for determining mechanical loads on an overhead power line

The most promising method for determining mechanical loads on a wire/cable is the inclinometry method based on measuring the angle of inclination of various objects relative to the gravitational field of the earth. As a verification method, a technique is being developed to determine the mechanical loads on a wire/cable depending on the angle of its rotation around its axis. In this case, the monitoring device should be installed in close proximity to the point of suspension of the wire/cable to the string of insulators on the anchor support (for example, 1 meter from the point of suspension of the wire/cable). This is possible due to the fact that when the wire/cable is stretched, its rotation around its axis is observed, which allows obtaining additional information, and therefore to improve the existing inclinometry method for determining the tension of the wire/cable from its angle of inclination.

The spiral shape that is attached to the wire when twisting a high-voltage wire/cable is subsequently maintained due to residual strains obtained by twisting. Stresses that occur in the wire during twisting are mainly driven by bending and torsion. If the stresses are within the elastic range, then the wire after the termination of the impact from external forces will restore its original direct shape. In fact, when twisting a wire/cable, its rods always get residual deformations [12].

Due to the presence of mechanical deformations during tension of the wire/cable, its rotation around its axis is observed, which allows obtaining additional information about the behavior of the wire/cable on the overhead power line and consider it not within a single span, but as a whole interconnected section with the redistribution of mechanical loads between spans.

The methodology for calculating mechanical loads on an overhead power line using the improved inclinometry method includes two stages: 1) the calibration stage; 2) the IRD calculation stage.

2.1. The calibration stage

In the absence of IRD, when calculating the length of an unstretched wire/cable, we use the theory of ideal cable (thread) to determine the unknown parameters [14].

The system of equations for fiber balance:

$$\begin{cases} u = \dfrac{1}{2}(\dfrac{l}{a} - \alpha^* q_0 L_0) \\ \operatorname{sh}(u) = \dfrac{L_0}{2a} \end{cases} \tag{1}$$

where l is the span length, m; q_0 is the gravity force referred to a unit of length of an unstretched wire/cable, N/m; $a = \dfrac{H}{q_0}$ is the ratio between the horizontal gravity force to the gravity force referred to a unit of length of an unstretched wire/cable; α^* is the specific relative elongation of cable/wire, N^{-1}; L_0 is the length of the unstretched wire/cable, m.

To simplify further calculations, a variable u is introduced [14]:

$$u = \ln \operatorname{tg}(\frac{\pi}{4} + \frac{\alpha}{2}) \tag{2}$$

where α is the wire/cable tilt angle at the suspension point.

Based on the system of equations of balance of the fiber balance, by means of exclusion of a and expression, L_0 we obtain the following expression for determining the length of an unstretched wire/cable at the current temperature:

$$L_0 = \frac{-u + \sqrt{2\alpha^* l \times q_0 \times \operatorname{sh}(u) + u^2}}{\alpha^* q_0} \tag{3}$$

Based on the fact that the length of the unstretched wire/cable is calculated according to its physicochemical characteristics at a temperature of 20 °C, it is necessary to take into account the change in the length of the unstretched wire/cable depending on the ambient temperature. In the formula listed above, the temperature dependence is observed for the parameter q_0 since when the length of the wire/cable changes, its linear mass also changes. Therefore, the gravity referred to the unit length of the unstretched wire/cable will be equal to:

$$q_0 = \frac{q_{0t}}{1 + \beta(t_1 - t_0)} \tag{4}$$

where q_{0t} is the gravity force referred to the unit of length of the unstretched wire/cable (obtained by multiplying the gravity acceleration by the linear mass of the wire/cable taken from the handbook) [15]; t_0 is the temperature of wire/cable fabrication, °C; t_1 is the current temperature of wire/cable, °C; β is the temperature coefficient of linear elongation, °C^{-1}.

A wire/cable has the lowest intrinsic stress in the absence of external forces acting on it at the temperature of its fabrication. Therefore, it is necessary to divide the current length of the unstretched wire/cable to the length of the unstretched wire/cable at the temperature of its fabrication:

$$L_{0t} = \frac{L_0}{1 + \beta(t_1 - t_0)} \tag{5}$$

where L_0 is the length of the unstretched wire/cable at current temperature, m; L_{0t} is the length of the unstretched wire/cable at the temperature of its fabrication, m.

To reduce the possible error, the parameter L_{0t} should be averaged over the entire calibration period (overhead line operation time without IRD).

To describe the rotation of the wire/cable, a rope model should be considered [16].

At the ends of the rod span, the wires/cable are rigidly connected to each other and therefore receive the same end displacements, which means that in any section of the wire/cable along the length, all wires receive the same displacements. This means that due to the compatibility of the elastic displacements of the wire layers, despite the contact pressure between them, the internal friction forces can be neglected.

Thus, we obtain a generalized equation of static wire/cable:

$$\begin{cases} T = A \times \varepsilon + C \times \theta \\ M = C \times \varepsilon + B \times \theta \end{cases} \qquad (6)$$

where T is the gravity of wire/cable; M is the cross-section torque of wire/cable; A, B, C, are the generalized wire/cable stiffness factors;

$\varepsilon = \dfrac{ds - ds_0}{ds_0}$ where s ds is the longitudinal displacement of rods when the length of the wire/cable ds_0 changes; ε is the longitudinal deformation in the rod of wire/cable; θ is the angular deformation in the rod of wire/cable, $\theta = \dfrac{d\varphi}{ds_0}$, where $d\varphi$ is the angular displacement in rods w when the length of the wire/cable s_0 changes.

The generalized equation of wire/cable statics gives a complete description of its aggregate mechanical properties during tension and torsion. For a mechanical system, the number of degrees of freedom is equal to the number of joint equations describing its displacements under the influence of an external load. For a wire/cable, we have a system of two equations. Therefore, it acts as a system with two degrees of freedom, that is, all its mechanical properties are similar to that for an elastic system with two degrees of freedom.

To do this, we consider the main special cases of load on the wire/cable: pure tension and free tension.

Pure tension is observed when the wire/cable is stretched by force T when its ends are fixed from rotation ($\theta = 0$). This mode of mechanical loads is characteristic for the operation of the wire/cable in the spans with bushings. In this case, the following relations are obtained:

$$\begin{cases} T = A \times \varepsilon \\ M = C \times \varepsilon \end{cases} \qquad (7)$$

From the first equation it follows that the coefficient A is the elastic modulus of the wire/cable.

If in case of pure tension, one removes the securing of the second end of the wire/cable from rotation, then the wire/cable under the action of internal torque will unwind. This mode of mechanical loads is characteristic for the operation of the wire/cable in the spans with one passage and one anchor support. The external moment is zero ($M = 0$) This type of load is called free stretching.

Moreover, we obtain the following equalities:

$$T = (A - \frac{C^2}{B}) \times \varepsilon = (\frac{A \times B}{C} - C) \times \theta. \qquad (8)$$

The factor before ε characterizes the longitudinal displacement of the rods, and the factor before θ characterizes the angular displacement of the wires in the wire/cable. Based on this, we obtain the following equation for the dependence of the extension of the wire/cable on the angle of rotation around its axis, which is then simplified by dividing both parts by ds_0 and independently integrating both parts of the expression:

$$\int(A - \frac{C^2}{B}) \times ds = \int(\frac{A \times B}{C} - C) \times d\varphi \Rightarrow \Delta L = \frac{B}{C}\Delta\varphi \tag{9}$$

where ΔL is the change in length of wire/cable; $\Delta\varphi$ is the change in the rotation angle of the wire/cable around its axis.

To calculate the elongation of the wire/cable, we use the formula from the hyperbolic model of wire calculation [17]

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$$\Delta L = \frac{\alpha^*}{2} a \times q_0 \left[1 + L_0(\mathrm{ch}(u) - \alpha^* \times a \times q_0)\right]. \tag{10}$$

Thus, the identity in formula (9) takes the following form:

$$\frac{B}{C}(\varphi_1 - \varphi_0) = \frac{\alpha^* a \times q_0 \left[1 + L_{0t}(\mathrm{ch}(u) - \alpha^* \times a \times q_0)\right]}{2} \tag{11}$$

where φ_1 is the angle of rotation of the wire/cable around its axis at current mechanical loads on the wire/cable and the ambient temperature before IRD appearance; φ_0 is the initial angle of rotation of the wire/cable around its axis until the appearance of the IRD.

In expression (11), the coefficient of the ratio of horizontal gravity to gravity, referred to the unit length of the unstretched wire/cable, is determined as follows:

$$a = \frac{L_0}{2\mathrm{sh}(u)} \tag{12}$$

From formula (11) we take φ_0 and calculate it at the current temperature. At the same time, one should not forget to correct the gravity referred to the unit length of the unstretched wire/cable to its current temperature in accordance with formula (4).

To reduce the possible error in determining the initial angle of rotation of the wire/cable around its axis, the parameter φ_0 should be averaged over the entire calibration period (the period of overhead line operation without IRD).

Thus, the calibration step ends when determining the initial angle of rotation of the wire/cable around its axis, as well as the length of the unstretched wire/cable at its temperature of fabrication.

The stage of determining mechanical loads on an overhead power line by the improved inclinometry method

When the preconditions for the IRD formation (humidity above 80%, the temperature of the wire/cable is in the range from 0 to -5 °C) appear, the system for determining mechanical loads switches to control mode.

The simplification variable u is calculated by the formula (2) at the inclination angles of the wire/cable for cases of rapid increase in mechanical loads on the wire/cable (for example, the formation of IRD).

Next, the length of the unstretched wire/cable is calculated at the current temperature in relation to the length of the unstretched wire/cable at the temperature of its fabrication in accordance with formula (5):

$$L_{0g} = L_{0t}(1 + \beta(t_1 - t_0)) \tag{13}$$

In formula (11), we replace $a \times q_0$ with H and express the horizontal tension force of the wire/cable:

$$H = \frac{\alpha^*(1 + L_{0g} \times \mathrm{ch}(u)) - \sqrt{(\alpha^*)^2(1 + L_{0g} \times \mathrm{ch}(u))^2 - 8(\alpha^*)^2 L_{0g}(\varphi_1 - \varphi_0)\frac{B}{C}}}{2\alpha^* L_{0g}} \tag{14}$$

As a result, we find the gravity of the wire/cable:

$$T = H \times \text{ch}(u) \qquad\qquad (15)$$

For an overhead power line, it is the wire/cable tension parameter that is critical in terms of mechanical stress. Therefore, the process of determining mechanical loads on an overhead power line can be completed at this stage.

Results and discussion

The data obtained from monitoring systems include the error of the measuring sensors. Thus, the developed system for monitoring mechanical loads on a wire/cable has instrumental and methodological errors.

Instrumental errors include deviations of sensor readings. For this model, the following data is required: the angle of rotation of the wire/cable around its axis, the angle of inclination of the wire/cable and the temperature of the wire/cable. The maximum deviations in the readings of the sensors in the range of formation of ice deposits (from -20 to 0 °C, from 70 to 100% of relative humidity) are: ± 0.2 ° C for temperature; 0.0039 rad along the axes X and Y.

To test the method for determining the mechanical loads on the wires/cables of overhead lines, we calculated the steel lightning protection cable S-50 for an anchor span of 50 meters in length, where conditions for free rotation of the lightning cable under consideration appear. The length of the unstretched cable L_{0t} was taken equal to 50.1 m. The stiffness factors $A=9.196 \cdot 10^6$ N, $B=6.521$ N·m^2 and $C=5.994 \cdot 10^3$ N·m for the S-50 cable were taken from the table of the book "Steel hoisting ropes "[16] for the type of strand 1+6+12. In addition, the following S-50 cable parameters were used: $\beta = 12 \cdot 10^{-6}$ °C^{-1}, q_0 =4.094 N/m; φ_0 =0°.

As parameters for calculation mechanical loads on overhead power lines, the conditions for operating the overhead line at a temperature of -5 °C without IRD on the cable, as well as in the presence of an IRD with a diameter of up to 40 mm, were selected[1] [18].

The load from ice formations on the cable was calculated by the following formula

$$T_g = q_{0g} \times 9.8 \times \pi \times c \times (d_{\text{cab}} + c) \times L_{0g} \qquad\qquad (16)$$

where q_{0g} is the IRD density (900 kg/m^3); c is the thickness of the icy socket, m (c =0.01545 m); d_{cab} is the wire diameter, m (for S-50 d_{cab} = 0.0091 m).

Thus, the load from an IRD with a diameter of 40 mm on the S-50 cable at a temperature of -5 °C is 526.6 N.

In the absence of IRD on the cable, the angle of rotation of the cable around its axis is 3.452 rad, and the angle of inclination of the cable is 0.103 rad. When an icy socket with a diameter of 40 mm appears on the cable, the rotation angle of the cable around its axis is 101.984 rad, and the angle of inclination of the cable is 0.153 rad.

Based on formulas (14) and (15), we find the value of the tension force of the wire/cable:

$$T = \frac{(1 + L_{0g} \times \text{ch}(u)) - \sqrt{(1 + L_{0g} \times \text{ch}(u))^2 - 8L_{0g}(\varphi_1 - \varphi_0)\dfrac{B}{C}}}{2\alpha^* L_{0g} \times \cos(\alpha)} \qquad (17)$$

The resulting dependence of the obtained tension force of the cable on the angle of its rotation shown in the figure.

The tension strength of the wire/cable depends on 3 parameters: the angle of rotation of the wire/cable around its axis, the angle of inclination of the wire/cable and the temperature of the wire/cable. Therefore, when calculating the error, it is necessary to take into account the influence

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[1] PUE. 7-nd. Pt. 2.5. Vozdushnye linii elektroperedachi napryazheniem vyshe 1 kV. M.: OAO «VNIIE», 2003. Available at: https://www.ruscable.ru/info/pue/2-5.html.

of these parameters on the result of calculating the tensile strength of the wire/cable:

$$\Delta T = \frac{dT}{df}\Delta\varphi + \frac{dT}{d\alpha}\Delta\alpha + \frac{dT}{dt}\Delta t \qquad (18)$$

where Δt Is the deviations in the readings of the temperature sensor in the range of ice formation.
The error of the developed method [18] was analyzed by comparing it with the previously developed method for monitoring ice on the wires of an overhead power line. The algorithm for calculating the error of the previously developed methodology is described in detail in the dissertation "System for the automated monitoring of ice deposits of overhead power lines based on the inclinometry-meteorological method" [19].
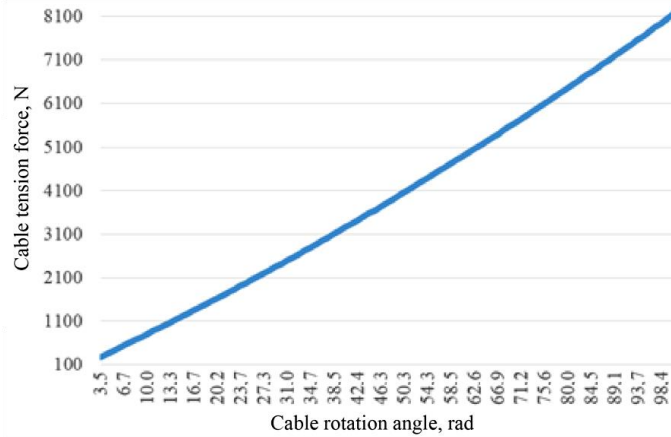

Fig. Relationship between the tension force of the cable and the rotation angle

For the conditions described earlier in this article when calculating the mechanical loads on the S-50 cable, the error of the developed method (taking into account the angle of rotation of the wire/cable around its axis) and the method developed earlier (excluding the rotation of the wire/cable around its axis), amounted to 0.46% (1.27 N) against 42.6% (118 N) with a minimum load and 0.04% (3.55 N) against 2.2% (183.94 N) when an icy socket with a 40 mm diameter appeared on the cable, respectively.

A comparison of the classical inclinometry and the developed methodology, taking into account the rotation of the wire/cable, is used as an example for calculating the S-50 by such characteristics as sensitivity and errors, in the range of operation from the minimum load to the load when an ice- socket with a diameter of 40 mm is formed on the cable is presented in the table.

Table

Comparison of the classic and developed methods that take into account the rotation of the cable

Characteristics	Classic	Developed
Temperature sensitivity, N/ºC	45	0. 05
Inclination angle sensitivity, N/deg	2230 ÷ 3375	4 ÷ 17
Rotation angle sensitivity, N/deg	No	1. 4
Error of the method, %	2. 2 ÷ 42.6	0. 04 ÷ 0. 46

Thus, the developed method for control the mechanical parameters of overhead power lines, taking into account the rotation of the wire/cable around its axis, is more accurate than the IRD determination method developed previously [21]. However, in practice, it is possible to use this technique based on the improved inclinometry method for the rotation angles of the wire/cable up to 180 º, which is due to structural limitations of the rotation of the wire/cable when attaching it to the support. In this case, the initial angle of rotation of the wire/cable is taken equal to 0º

degrees when the tension force of the wire/cable is close to the mounting one and at the temperature of this wire/cable fabrication. Thus, the diameter of the ice-clutch for calculating the S-50 ground wire in this article should not exceed 12.5 mm and is made only for flights with one anchor support.

Conclusions

A method has been developed for determining mechanical loads on wires/cables of overhead lines based on mathematical models of ideal cable, rope and a model for determining ice deposits on wires [15–17,20], taking into account the rotation of the wire/cable around its axis. This method allows more accurate determining the elongation of the wire/cable in the span with one anchor support, as well as the its tension force, however, it requires additional refinement related to the influence of the wind, the formation of IRD of various shapes, as well as structural limitations of the rotation of the wire/cable when attaching it to the support. The implementation of this technique will allow monitoring the mechanical parameters of wires/cables, as well as identifying areas with the formation of IRD in the early stages in order to prevent related emergencies.

The methodology for monitoring the mechanical parameters of overhead power lines based on the improved inclinometry method is the result of studies described in [17, 20]. For the practical implementation of the method, a technical solution was developed in the form of a measuring device for monitoring the mechanical parameters of an overhead power line [21].

The developed methodology for determining the mechanical loads on the wires/cables of overhead lines and the mathematical model are tested on the SMG-16 system, which was put into trial operation at PJSC Tatneft.

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